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Nanosecond pulsed laser texturing of optical diffusers

Tawfiq Alqurashi,[1,2,a] Aydin Sabouri,[1] Ali K. Yetisen,[3] and Haider Butt[1,b]
[1]*School of Engineering, University of Birmingham, Birmingham B15 2TT, United Kingdom*
[2]*Department of Mechanical Engineering, School of Engineering, Shaqra University, P.O. Box 90, Dawadmi 11921, Saudi Arabia*
[3]*Harvard-MIT Division of Health Sciences and Technology, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

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High-quality optical glass diffusers have applications in aerospace, displays, imaging systems, medical devices, and optical sensors. The development of rapid and accurate fabrication techniques is highly desirable for their production. Here, a micropatterning method for the fast fabrication of optical diffusers by means of nanosecond pulsed laser ablation is demonstrated (λ=1064 nm, power=7.02, 9.36 and 11.7 W and scanning speed=200 and 800 mm s^{-1}). The experiments were carried out by point-to-point texturing of a glass surface in spiral shape. The laser machining parameters, the number of pulses and their power had significant effect on surface features. The optical characteristics of the diffusers were characterized at different scattering angles. The features of the microscale structures influenced average roughness from 0.8 µm to 1.97 µm. The glass diffusers scattered light at angles up to 20° and their transmission efficiency were measured up to ~97% across the visible spectrum. The produced optical devices diffuse light less but do so with less scattering and energy losses as compared to opal diffusing glass. The presented fabrication method can be applied to any other transparent material to create optical diffusers. It is anticipated that the optical diffusers presented in this work will have applications in the production of LED spotlights and imaging devices. [http://dx.doi.org/10.1063/1.4977743]

INTRODUCTION

Optical diffusers are widely used to distribute the light intensity from a focused light source to expand the beam.[1,2] Optical diffusers are categorized according to their characteristics to distribute radiant energy effectively from an incident source in the far field.[3] Their applications range from photovoltaic devices, optical imaging, photolithography to photodynamic therapy.[4] Moreover, optical diffusers are one of the essential components in liquid crystal displays (LCDs).[5–7] The diffusion of light can be achieved either from a surface or through volume of optical element. It may comprise of incorporated micro- and nanoparticles or structured patterns.[4,8] Most diffusers consist of surface-relief structures including microlenses, pyramids, and textured surfaces due to the simplicity and time required for their fabrication.[9–13] Optical diffusers have been fabricated employing a range of coating processes.[5,14] However, nanosecond pulsed laser patterning of optical diffusers have not been studied. This technique can enable the fabrication of optical diffuser by direct material structuring or texturing without any coating processes.

However, the fabrication of optical diffusers by nanosecond laser sources have not been exploited as it has challenges compare to conventional continuous wave (CW) lasers.[15] The demand for laser manufacturing methods has increased as a result of fast growing optoelectronics market.[16] The

[a]talqurashi@su.edu.sa
[b]h.butt@bham.ac.uk

direct laser manufacturing: (i) enables the flexible production of complex geometries;[17] (ii) offers fast fabrication route compared to conventional techniques, (iii) is more environmentally friendly compared with coating processes; and (iv) provides precise control over the size and shape of the microstructures.[18] At the same time, the engineering applications of optical diffusers depend on their homogenization, performance, and efficiency.[19] Optical diffusers can spread light in one or two dimensions depending on their applications.[20]

In this research, we report the fabrication of optical diffusers by using nanosecond laser induced surface texturing. This method differs from other techniques used for producing holographic diffusers, where a pulsed laser is used for patterning a photopolymer layer coated onto a plastic or glass substrate.[21,22] In contrast to this, we perform direct laser ablation of float glass substrates (without any polymer coating) for the production of tailored surface textures and roughness. The proposed new fabrication approach allows functional microstructures (topographies) to be created on float glass substrates to distribute light efficiently. The produced optical diffusers were characterised by using angle-resolved optical power intensity and spectroscopy analysis to assess the light scattering and transmission efficiency. In addition, the diffusers' three-dimensional light distribution was captured *via* a digital camera to analyse their light transmission properties. Additionally, Alicona G5 Infinite Focus (IF) system was employed to analyze the surface topographies (roughness) of the optical diffusers.

OPTICAL DEVICE FABRICATION

To fabricate diffusers, a float glass slide (1 mm thickness) was used as a substrate to create the surface micro structures. The surface patterning was performed using a master oscillator power amplifier (MOPA) based Yb fiber laser (λ=1064 nm). The micro groove structures on the glass substrate were produced, point-to-point texturing a glass surface in a spiral pattern, using three different power levels, i.e. 11.7, 9.3, and 7.02 W. A scan head and 100 mm telecentric focusing lens were included in the beam delivery system to focus the beam and two different scanning speeds, i.e. 200 and 800 mm s^{-1}, were used in this feasibility study.

After the laser texturing operation the micro surface structures on the glass slides were analyzed employing the Alicona G5 InfiniteFocus (IF) system and thus to measure the average roughness (Ra). Table I Shows the effects of varying laser power and scanning speeds on the resulting surface roughness. The increasing of pulse energy led to an increase of grooves' depth and increased the average roughness. Higher pulse energy resulted in material splashes over the edge of the grooves. The micro surface structures of glass substrates produced with investigated laser power levels and scanning speeds are shown in Figure 1. Depending on the laser power and scanning speed, the depth and distance of the grooves can be controlled to achieve accurate spiral shapes. However, exceeding 11.7 W at scanning speed of 200 mm s^{-1} may destroy the substrate (Figure 1a). Hence, the experimental parameters were optimized not to pass this average power threshold. These results provide some insight into the laser settings required to create optical diffusers as the roughness of the textured surfaces affects their performance.[23,24] The interaction of the fabricated grooves with a beam of light diffuses the photons and expands the focused beam.

TABLE I. Average roughness for the spiral pattern diffusers with various average powers and scanning speeds.

Machining Power (W)	Scanning speed (mm s^{-1})	Average roughness (μm)
11.7	200	1.97
11.7	800	1.64
9.36	200	1.66
9.36	800	1.61
7.02	200	1.16
7.02	800	0.8

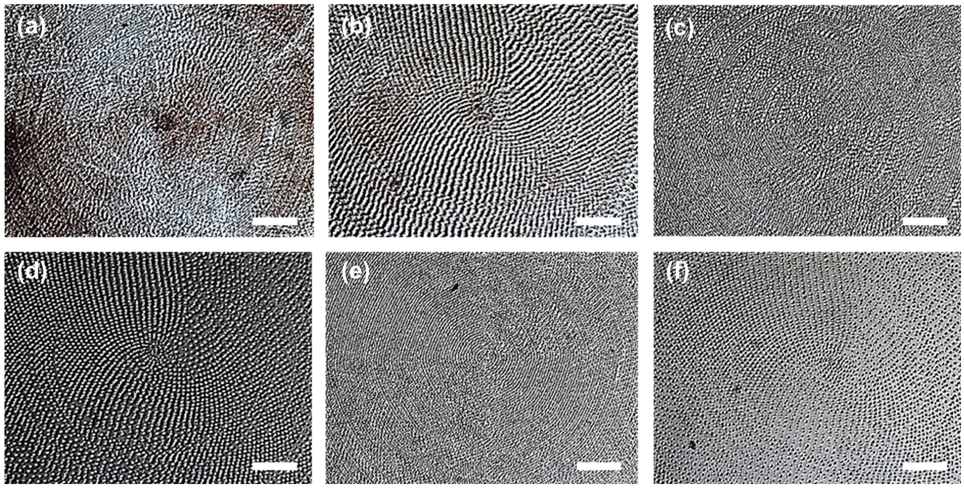

FIG. 1. The micrographs of textured glass substrates with different laser powers and machining speeds: (a) 11.7 W, 200 mm s^{-1}, (b) 11.7 W, 800 mm s^{-1}, (c) 9.36 W, 200 mm s^{-1}, (d) 9.36 W, 800 mm s^{-1}, (e) 7.02 W, 200 mm s^{-1}, and (f) 7.02 W, 800 mm s^{-1}. Scale bar= 200 μm.

OPTICAL CHARACTERIZATION

To characterize the optical performance, micropatterned glass samples were cleaned with isopropyl alcohol and dried before characterization. The light diffusion from the samples was characterized by two set of experiments. The diffusers were placed onto a post with a semi-transparent hemispherical screen set above it. The radius of the hemispherical screen was 15 cm. This setup allowed for capturing the diffraction pattern in the far field because of the sufficient distance from the sample to the hemispherical screen surface.[3] The plane of the sample was placed to be

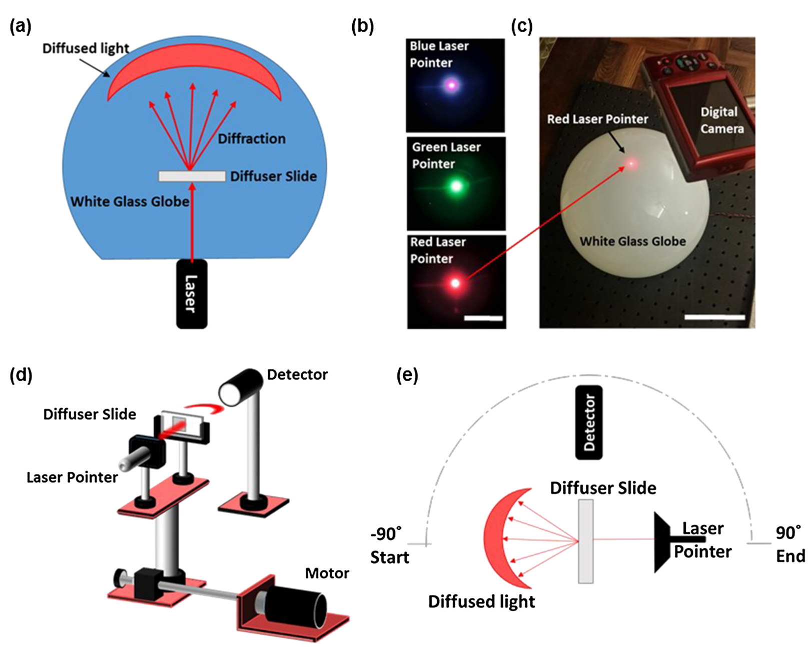

FIG. 2. Optical characterization of the diffusers using angle-resolved measurements. (a) Schematic of globe diffusion measurements. (b) The output of three laser beams projected on the screen (Scale bar= 1 cm). (c) The image of the globe setup (Scale bar= 12 cm) (d). The schematic of the angle-resolved diffusion measurements. (e) The top view of angle-resolved light transmission setup.

parallel to the base of the screen (Figure 2a). The laser was placed below the sample, laser beam set to be 1 mm wide and normally incident to the sample. The laser light was transmitted vertically toward the hemispherical screen. A digital camera was used to capture the produced diffraction patterns.

Angle-resolved measurements were performed to characterize the angular distribution of diffused light (Figure 2b). The setup consisted of three laser sources (λ=450, 533 and 633 nm), diffuser sample, an optical power meter to detect the intensity of the scattered light at different angles and a servo motor to rotate the sample. The light source and the sample rotated together on the same base so

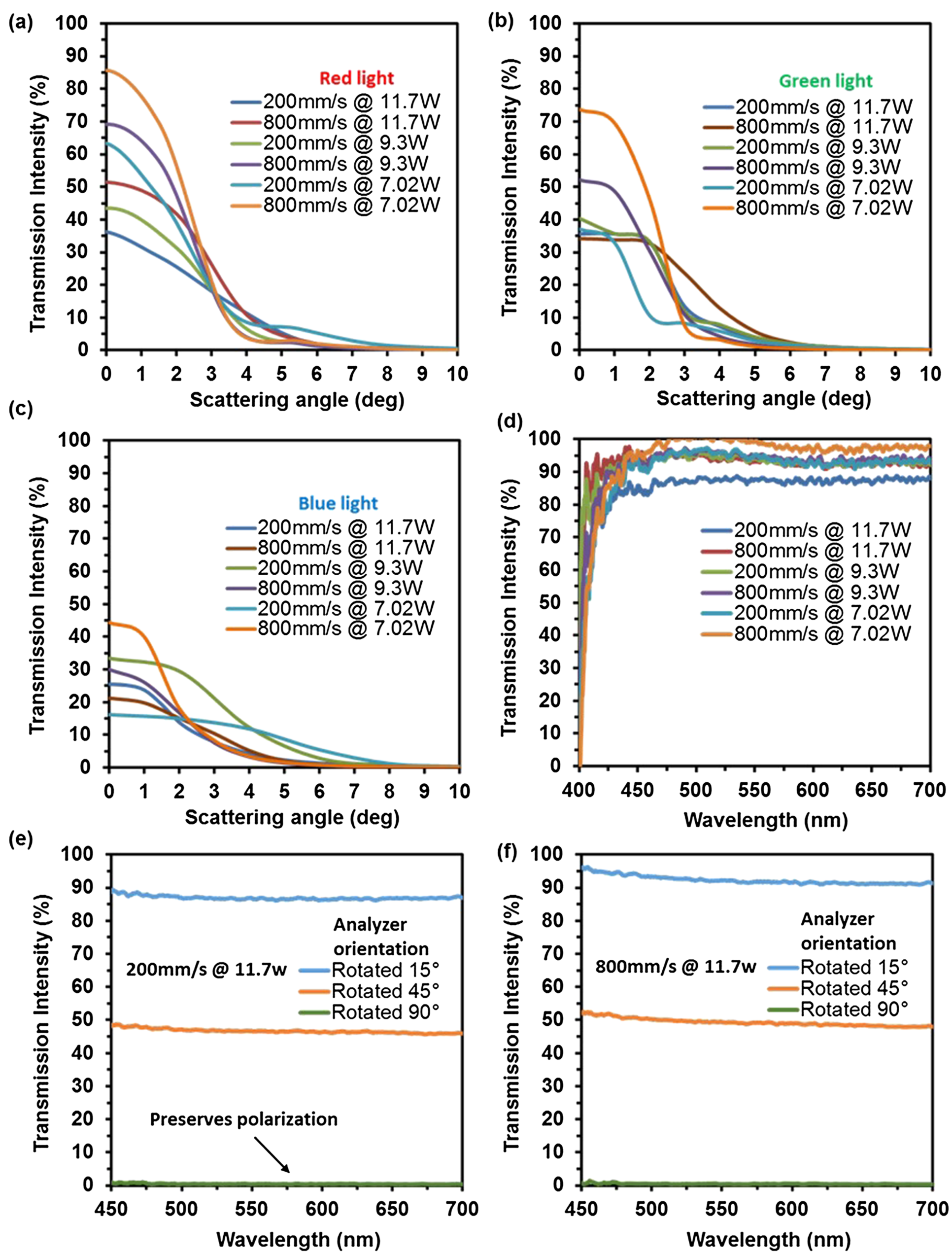

FIG. 3. Transmission spectrum of various diffusers machined by a nanosecond laser. (a-c) Angle-resolved measurements of the optical diffusers by using different laser beams (633 nm, 533 nm, and 450 nm). (d) Spectroscopic measurements of the optical diffusers using a broadband light and the light intensities in transmission mode. (e and f) Polarised spectroscopic measurement of the optical diffusers using analyser and polarizer oriented at 15°, 45° and 90°.

the incident light remained normal to the sample. The rotations were performed in 1° increments, to allow that the intensity of light can be measured at every single angle.

Figure 3a–c shows the diffusion efficiency of the textured surfaces on glass substrates. The diffusers textured with lower energies had higher intensity values at central peaks. Slower scanning speed resulted in lower peak intensities in the central region and consequently provided wider light transmission. The depth of grooves changed the transmission intensity from 35 to 65%, a deeper grooves resulted in intensity decrease. Generally, the diffusers had scattering angle in range of 14° to 20° and their intensities had been in range of 35 to 85%. Once the light wavelength was reduced, both the scattering and their intensities were reduced, respectively. Additionally, Figure 3d shows that the lowest transmission was recorded for the highest scanning speed with lowest power, while the highest transmission was recorded for the lowest scanning speed with highest power. They diffuse light less but do so with less scattering losses which result in less energy losses as compared to opal diffusing glass. This is due to changing the roughness of the surface and the number of grooves per unit area, where lowest roughness and less number inscribes of surface have higher light transmission intensities.

Furthermore, we also tested the polarization dependence of the diffusers. A polarized optical microscope was used to carry out cross polarized transmission measurements on the diffuser samples. The diffuser samples were placed between the analyzer and polarizer and the corresponding transmission spectra were measured using an integrated spectrophotometer (2 nm resolution). The measurements were performed at analyzer/polarizer orientation angles of 15°, 45° and 90°. Over 90% transmission was observed at an orientation angle of 15° (Figure 3e–f). Transmission reduced to near 50% and 0% for the orientation angles of 45° and 90°. This signified the diffused light had the same polarization as the incident light, hence the polarization was preserved.

To compare the transmission efficiency of diffusers with various machining parameters, the total number of transmitted photons was calculated. Figure 4 shows the efficiency of fabricated diffusers which were achieved by the integration of transmission spectra. By increasing the laser power for material ablation, the transmission efficiency of the diffusers decreased (Figure 4a). This was due to increase in material removal rate and producing the rougher surfaces, which was consistent with the performed roughness measurements. Similarly, faster texturing produced smoother surfaces, which resulted in less light scattering and consequently increased the transmission efficiency (Figure 4b).

Figure 5 shows the three-dimensional distribution of the diffused light for laser wavelengths of 450, 533 and 633 nm. When the laser beams were transmitted through the glass diffuser, the light scattered at small angles, but with high transmission of light. Increasing the laser beam wavelength increased the angle of light diffusion (as also shown in figure 3a to 3c). The results show that such optical diffusers can be used in LED screens and spotlights for producing soft light. Although, in this research, we studied circular surface patterns produced on glass substrates, the laser processing unit

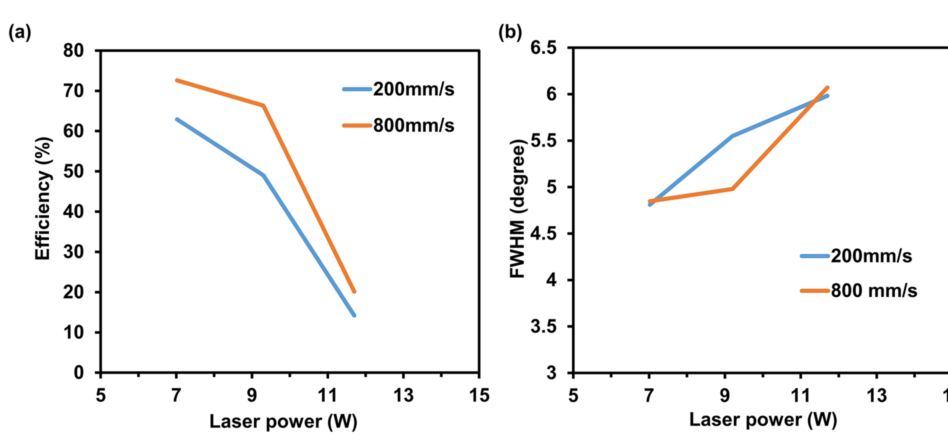

FIG. 4. The effect of laser light power and scanning speed on light transmission intensity of machined optical diffusers. (a) Light transmission efficiency of the optical diffusers. (b) The full width at half maximum of the diffracted spectrum from the optical diffusers.

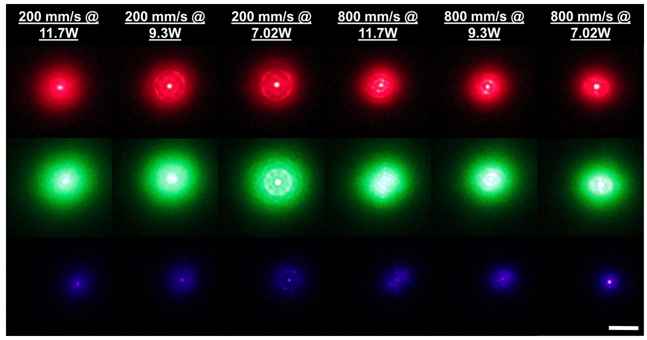

FIG. 5. Different laser beams (450, 532, and 635 nm) were transmitted through the optical diffusers, producing circular diffusion patterns. The nanosecond laser parameters used for producing the diffusers are listed. Scale bar=1.5 cm.

is capable of 5 axis motorized motion and can produce a variety of sophisticated one/two dimensional surface patterns. By producing custom-designed surface patterns, we can produce diffusers, which will enable high performance, and tailored light distribution and intensity profiles.

CONCLUSION

The micro surface features of the textured glass slides were investigated using Alicona microscope system and showed that it has a direct relation with power and inversely related to the scanning speed. The characteristics of the optical diffusers patterned by this method can be altered by changing the laser machining parameters. The faster laser machining along with lower ablation energies produces the diffusers with higher efficiency and wider scattering patterns. By increasing the roughness area of surface, the distribution of light can be precisely controlled in wide ranges. The conducted study showed quick and efficient fabrication of spiral textured patterns as optical diffusers using a nanosecond laser by inscribing the surface of glass. Such glass diffusers may be utilized in headlights. Producing thin optical diffusers using nanosecond laser ablation may achieve high light transmission and less energy consumption in consumer electronics.

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